Reports File

B-716

GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: April 15, 1971

Project Title: Research Initiation - Distortion Effects of a Second Harmonic Generator on a Mode-Locked Pulse Train from a Nd:YAG Laser

Project No: B-716 (See E-21-609)

Principal Investigator Dr. William R. Callen, Jr.

Sponsor: National Science Foundation

Agreement Period: From April 1, 1971 Until September 30, 1972

Type Agreement: Grant No. GK-27814

Amount:

$16,000	NSF Funds (B-716)
4,653	Ga. Tech Contribution (E-702)
$20,653	Total

Reports Required: Annual Letter Technical (short, informal) due March 31, 1972.
Final Letter Technical due upon completion (September 30, 1972).

Sponsor Contact Person (s):

National Science Foundation
Division of Engineering
Attn: Royal E. Rostenbach - Engineering Energetics Program
Washington, D.C. 20550

Assigned to: School of Electrical Engineering

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RA-3 (2-71)

GEORGIA INSTITUTE OF TECHNOLOGY

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RESEARCH PROJECT TERMINATION

Date: February 21, 1973

Project Title: Research Initiation - Distortion Effects of a Second Harmonic Generator on a Mode-Locked Pulse Train from a Nd:YAG Laser

Project No: E-21-609

Principal Investigator: Dr. William R. Callen, Jr.

Sponsor: National Science Foundation

Effective Termination Date: 3/31/73

Clearance of Accounting Charges: 3/31/73

Grant/Contract Closeout Actions Remaining:

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E-21-609

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

SCHOOL OF
ELECTRICAL ENGINEERING

March 29, 1972

National Science Foundation
Division of Engineering
Washington, D. C. 20550

Attention: Royal E. Rostenbach
Engineering Energetics Program

Subject: Research Initiation Grant No. GK-27814
Interim Report

Gentlemen:

Enclosed is our informal technical letter describing progress on the research "Investigation of the Distortion Effects of a Second Harmonic Generator on a Mode-Locked Pulse Train from a Nd:YAG Laser."

We feel that the work will be completed as proposed and appreciate the opportunity provided by this grant.

Sincerely,

W. R. Callen
Assistant Professor

WRC/bew

Enclosure

The investigation sponsored by this contract is the study of the distortion effects of a second harmonic generator on the output of a Nd:YAG laser which is simultaneously mode-locked and Q-switched by a saturable absorber. In particular, the effect of the phase matching condition on very narrow pulses is being studied.

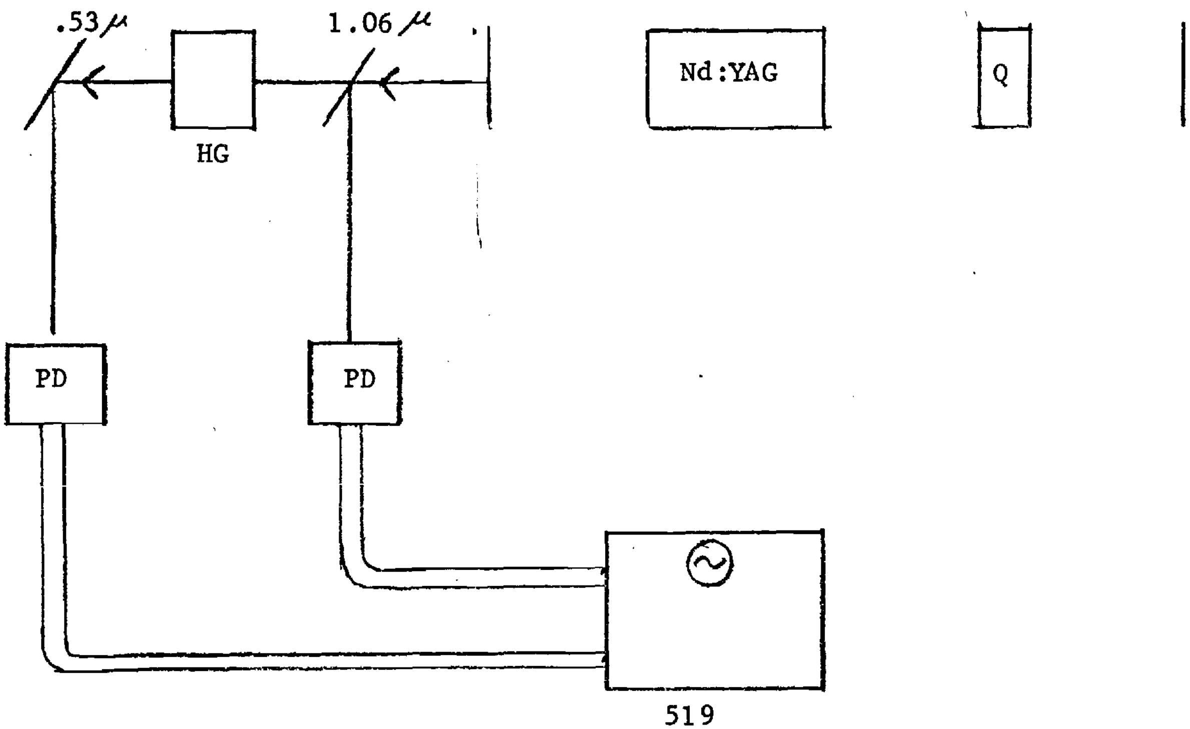
The third quarter of research is now beginning. The principal investigator spent the summer quarter of 1971 at Marshall Space Flight Center in Huntsville, Alabama performing research in optical data processing, a related field of endeavor. During the fall and winter quarter, the principal investigator worked approximately one-half time and full time, respectively.

A large fraction of the effort on the initial phase of the research has been to assemble the necessary equipment to perform the research. Rather than modify the ruby laser which was described in the original proposal, we have decided to obtain another laser through in-house funds. This laser is being purchased from Q. E. D. Corporation and will be capable of twenty pulses per second repetition rate with a supply voltage stability of better than .1%. We feel that this small shot-to-shot variation will play an important role in our future study. The laser cavity will contain a 2 1/2" by 1/4" flat anti-reflection coated Nd: YAG rod. The laser has been ordered and its arrival is expected during the coming quarter.

A schematic diagram of the initial experiment to be performed is shown in Figure 1. Both the fundamental and second harmonic pulse trains will be monitored by fast photodiodes and displayed on the Tektronix

519 oscilloscope. After this system is in operation, detailed monitoring of the pulse train will be attempted.

Although the emphasis of the research is experimental, some theoretical effort has begun on attempting to obtain a more thorough understanding of the harmonic generation process. During the coming year we will proceed along these lines.



Q - Q-switch Cell
HG - Harmonic Generator
PD - Fast Photodiode
519 - Tektronix 519 Oscilloscope

Figure 1 INITIAL EXPERIMENT

Research Initiation Grant GK-27814

INVESTIGATION OF THE DISTORTION EFFECTS OF A SECOND HARMONIC GENERATOR ON A MODE-LOCKED PULSE TRAIN FROM A Nd:YAG LASER

W.R. Callen and J.E. Weaver
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1973

FINAL REPORT FOR PERIOD 1 APRIL 1971 – 3 MARCH 1973

Performed for
National Science Foundation
Division of Engineering
Washington, D.C. 20550

INVESTIGATION OF THE DISTORTION EFFECTS OF A SECOND HARMONIC GENERATOR ON A MODE-LOCKED PULSE TRAIN FROM A Nd:YAG LASER

By
W. R. Callen and J. E. Weaver
School of Electrical Engineering

FINAL REPORT
RESEARCH INITIATION GRANT GK-27814
1 April 1971 to 3 March 1973

Performed for
NATIONAL SCIENCE FOUNDATION

GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

ABSTRACT

The distortion effects of a second harmonic generator on a mode-locked pulse train from a Nd:YAG laser is investigated. Possible sources of the distortion are compared and the relative magnitudes of the effects are discussed. A Nd:YAG laser system has been constructed for this investigation. Closely related future experiments are described.

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I. INTRODUCTION

For a practical, high bit rate, digital communication system using lasers, the laser transmitter must be capable of producing a train of short pulses of high peak power. This requirement is most nearly met by a mode-locked laser. Mode-locked lasers have produced pulses with peak powers in excess of 10^8 watts with full widths of less than one hundred picoseconds.

A particularly attractive laser for such a communication system is the Nd:YAG laser operating at a wavelength of 1.06 microns. Although the Nd:YAG laser has a narrower linewidth, and therefore does not exhibit pulses as short as those achieved by using Nd:glass as the active medium, the YAG laser is of more interest in a communication system. Nd:YAG is much more stable with respect to thermal distortion caused by the heating effect of repetitive Q-switching, which would probably occur in an applied system. The longer pulse width of Nd:YAG is not a real limitation, as pulses as short as eighty picoseconds have been observed, which one researcher estimates could form the basis of a possible 10^4 megabits per second optical pulse code modulation communications system.[1]

Most communication systems using Nd:YAG as a laser transmitter frequency double the output to $\lambda = .53\mu$. This wavelength lies in the center of the visible spectrum, where detection sensitivity is high.

Although the efficiency of second harmonic generation is extremely high, it may produce distortions in the picosecond pulse train. It has been the objective of this research to investigate the effects of second harmonic generation on mode-locked pulses and to initiate an experimental investigation of second harmonic generation of a mode-locked pulse train.

II. SECOND HARMONIC GENERATION AND DISTORTION

A. Second Harmonic Generation

The following requirements must be met for efficient second harmonic generation to occur in an anisotropic medium:

1. The medium must not exhibit inversion symmetry. This property is a consequency of the fact that even-order susceptibility tensors vanish in a medium with inversion symmetry. Since all materials studied do lack inversion symmetry this property is not directly considered in relation to pulse distortion.

2. The medium must be sufficiently transparent at both the fundamental and second harmonic frequencies. Absorption at either frequency produces heating. This source of distortion is discussed in Section II C.

3. The fundamental and the second harmonic beams must traverse the same path in the medium, and the second harmonic generated along the path must remain in phase. This is accomplished by balancing the natural dispersion of the crystal with birefringence. This technique, known as phase matching, may be achieved either by applying an external electric field, by temperature tuning, or by using specified propagation orientations. Departure from perfect phase matching, known as "mismatching" is discussed in Section II D and is an important source of waveform distortion, particularly for ultrashort pulses.

The basic theories of harmonic generation, mode-locked lasers, and ultrashort pulses have been the subjects of extensive review articles and are, therefore, not discussed in this report. [2, 3, 4]

B. Non-Linear Gain

In general, the second harmonic power generated is proportional to the square of the power at the fundamental.

$$P^{2\omega} = G(P^{\omega})^2$$

If a pulse of light is frequency doubled, then this non-linear gain leads directly to a shortening of the pulse. This shortening, which may be on the order of 20% for a typical pulse is intrinsic to the harmonic generation process and, therefore, is not considered as a true source of distortion.

C. Thermal Effects

Due to finite absorption at both the fundamental and second harmonic, local heating will be produced by the laser beam. Most materials used in harmonic generation exhibit a negative refractive index change with temperature, resulting in a thermal self defocussing of the beam. This thermal defocussing spreads the beam and can lead to a significant distortion in the beam profile. Typically, thermal defocussing is overcome in practive by prefocussing the laser beam into the nonlinear crystal. [5] The thermal defocussing tends to extend the waist region (assuming a Gaussian beam profile) to include the entire length of the crystal. This technique has been used to increase the power density within the crystal to the point of inducing permanent damage. Increases in the conversion efficiency by a factor of 3×10^3 have been recorded.

Although the prefocussing tends to greatly reduce thermal blooming, the effect has been observed in the focussed beam of a pulsed laser. [6] In that experiment, the minimum pulse lengths reported to exhibit thermal blooming was on the order of 1 μ sec, approximately 1/10 of the hydrodynamic time, τ_h, the time for a pressure disturbance to cross the laser beam. Since mode-locked pulses from a Nd:YAG laser have a duration $\tau_p \sim 100$ psec $= 10^{-10}$ sec, their duration is 10^{-4} times the minimum duration pulse for which thermal blooming has been observed. For such pulses where $\tau_p << \tau_h$, significant thermal blooming is not expected to occur, but this perhaps could be the subject of future research.

D. Pulse Distortion due to Mismatching

For the case in which the fundamental and second harmonic waves propagate with different refractive indices, the second harmonic conversion efficiency can be shown to vary as:

$$\eta_{SHG} = \frac{P_{2\omega}}{P_\omega} \propto (X^{2\omega})^2 \frac{\sin^2 \frac{\Delta K l}{2}}{(\Delta K l/2)^2} \frac{P_\omega}{A},$$

where $P_{2\omega}$ and P_ω are the powers at the second harmonic and fundamental, respectively, $X^{2\omega}$ is the second order nonlinear susceptibility, l is the length of the crystal, ΔK is the mismatch between the second harmonic and the fundamental $(K^{2\omega} - 2K^{\omega})$, and A is the area of the beam cross section. [7, 8]

From the above expression it is seen that for efficient conversion of the fundamental to the second harmonic $\Delta K = 0$, or $K^{2\omega} = 2K^{\omega}$. Normally this condition is achieved by launching, for example, the fundamental wave as an ordinary ray in the crystal and the second harmonic wave as an extraordinary ray. Since in normally dispersive materials the refractive index increases with frequency, it is possible to balance birefringence with dispersion and achieve $\Delta K = 0$ for a given frequency and a given propagation direction.

Physically, the generation of a short pulse requires the synthesis of a range of frequencies approximately $\Delta f \sim \frac{1}{\tau}$, where τ is the length of the pulse. For $\tau \sim 10^{-10}$ sec., this requires a frequency spread of $\Delta f \sim 10$ GHz. As such a pulse propagates through a frequency doubling medium, the phase matching condition will not be satisifed exactly over the entire frequency range of the pulse due to the dispersion of the frequency doubling material.

Two materials that have been used extensively for second harmonic generation are potassium dihydrogen phosphate (KDP) and lithium niobate ($LiNbO_3$). [5, 9, 10] In this research, $LiNbO_3$ has been emphasized because the distortion effect due to crystal dispersion is much greater in $LiNbO_3$ than in KDP. For comparison, the dispersions for $LiNbO_3$ and KDP are listed in Table 1. [10, 11] $LiNbO_3$ exhibits a second harmonic dispersion almost two orders of magnitude greater for the same orientations.

An in-depth analysis of the output spectra and time domain waveform for second harmonic generation in a non-linear medium by a broad-band pulse has been conducted by Glenn. [12] The fundamental (ordinary) and second harmonic (extraordinary) fields are expressed as Fourier transforms. The dispersion at the fundamental and second harmonic is included by decomposing each field into plane-wave components with a dependence $\exp i\,[k(\omega)\, z - \omega t]$ and including the dependence of k on ω. This type of calculation assumes no depletion of the fundamental wave. For two identical fundamental waves (both ordinary or both extraordinary) and a nonidentical second harmonic, two regions are of interest. For the case of near matching of the group velocities, the envelope of the output pulse is simply the square of the envelope of the input pulse. For extreme mismatch, the output is nearly a square pulse, and the duration increases in proportion to crystal length. If the second harmonic is

Table 1. Dispersion of $LiNbO_3$ and KDP

	$LiNbO_3$	KDP
$\frac{\Delta n_o^{2\omega}}{\Delta\lambda}$	45,600 cm^{-1}	565.4 cm^{-1}
$\frac{\Delta n_e^{2\omega}}{\Delta\lambda}$	44,000 cm^{-1}	421.9 cm^{-1}
$\frac{\Delta n_o}{\Delta\lambda}$	505 cm^{-1}	289.7 cm^{-1}
$\frac{\Delta n_e^{\omega}}{\Delta\lambda}$	445 cm^{-1}	110.9 cm^{-1}

produced by two nonidentical fundamental waves (one ordinary and one extraordinary), then it can be noted that the second harmonic pulse is stretched in time because of the properties of the nonlinear crystal and is independent of the bandwidth of the fundamental pulse. The change in duration of the second harmonic pulse on passage through the crystal relative to its original duration may be a function of bandwidth. For the case of a frequency chirped pulse, as has been shown to be the case of pulses from both mode-locked Nd:glass and Nd:YAG lasers, the second harmonic pulse consists of an unmodulated center section, with both ends of the pulse modulated. [13, 14, 15]

Other authors have studied the time domain stretching of second harmonic pulses in $LiNbO_3$ and KDP due to dispersion. Comly and Garmire calculated the broadening in time of the second harmonic pulse to be proportional to the crystal length in $LiNbO_3$. [16] Sharpiro observed picosecond pulses of duration tunable by crystal length in $LiNbO_3$ and suggested the existence of pulse substructure in ultrashort pulses produced in KDP. [17] Substructure in ultrashort laser pulses has been verified. [18, 19 20] Direct measurements of broadened second harmonic pulses from a Nd:glass laser have resulted in pulse widths varying from 3.8 psec to greater than 15 psec. [21]

E. Pulse Distortion Effects of an Intensity Dependent Refractive Index

Significant changes in the properties of a nonlinear material can be produced by the propagation of intense optical radiation through the material. These changes can, in turn, directly affect the radiation itself and can produce pulse distortion. Other phenomena, such as self phase-modulation, or self-steepening of light pulses, produced by an intensity dependent refractive index, as in the case of Kerr effect liquids, have been analyzed. [22, 23, 24]

Second harmonic generation also can produce self-phase modulation, although it is difficult experimentally to sort out this effect from the others previously discussed. [25, 26] It appears that amplitude modulation of the second harmonic pulse would occur, in addition to the broadening.

III. EXPERIMENTAL

A stable Nd:YAG laser Q-switched by a saturable absorber has been constructed, as shown in Figure 1. The laser head and power supply was purchased from Q.E.D. Corporation, and is capable of a twenty pulse per second repetition rate with a supply voltage stability of better than 1%. A frequency doubler using lithium niobate as the nonlinear crystal with a temperature controlled oven has been designed. EG & G fast photodiodes are used to monitor the fundamental and second harmonic pulse trains. Our laboratory now possesses the major pieces of equipment shown in Table 2.

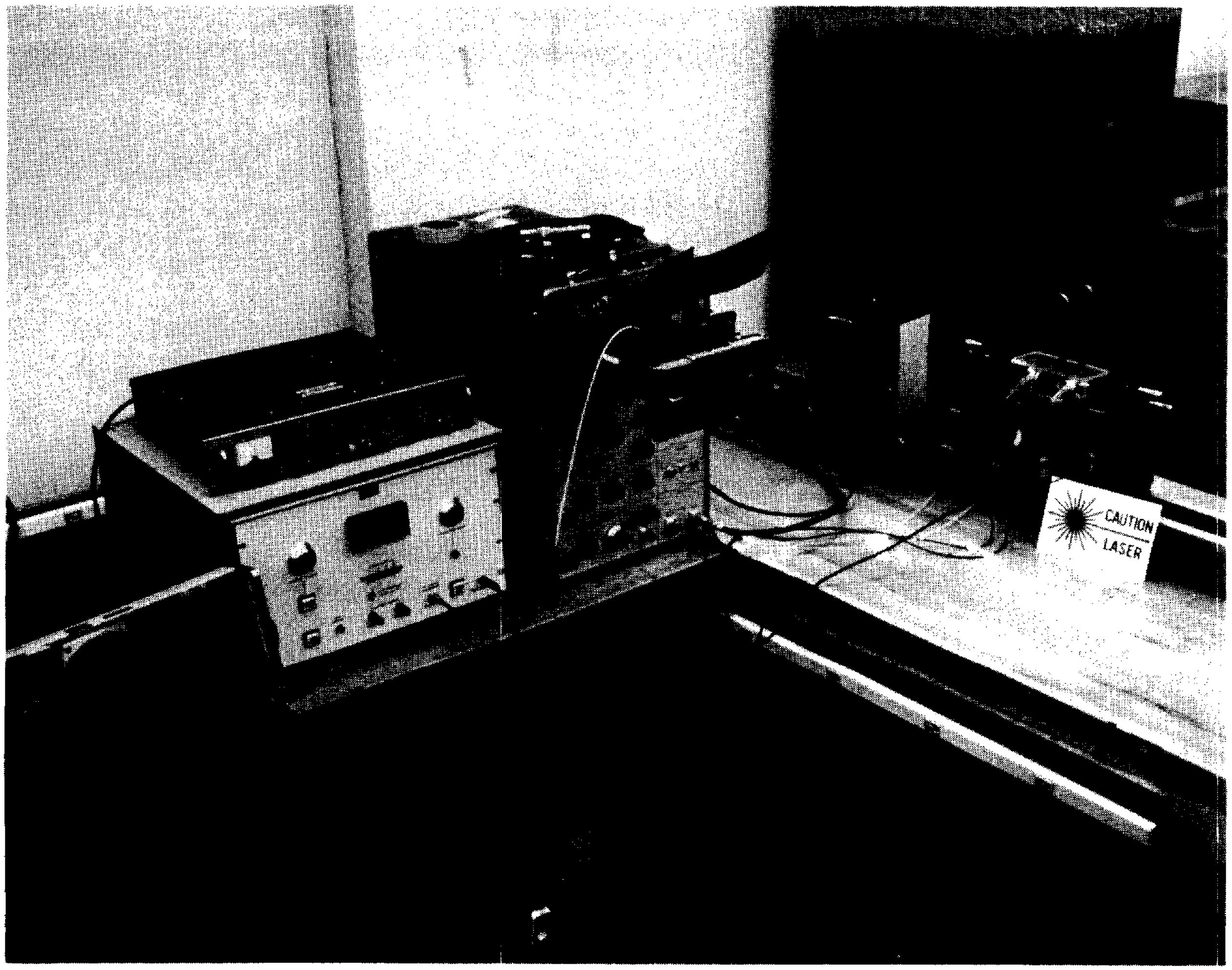

FIGURE 1. Nd:YAG Laser

Table 2. Related Equipment Obtained During Grant

Q.E.D. Nd:YAG Laser

EG & G Fast Rise-Time Photodiode
(S-1 surface)

EG & G Fast Rise-Time Photodiode
(S-20 surface)

Fluke Power Supply Model 415B

Fluke Power Supply Model 415B

Tektronix 519 Oscilloscope

Tektronix C-27-662R Camera

Ealing Neutral Density Filters

Scientech Optical Bench

Kodak Q-Switching Solution

Kodak Q-Switching Cell

Complete Tool Set

Airtron YAG Laser Rod

IV FUTURE EFFORTS

Future efforts are expected to focus on two areas:

(1) A continuation of the initial overall program as outlined, involving the establishment of a reliable picosecond pulse system and the investigation of the frequency doubling process. Theoretical efforts on the distortion problem could include modifying Glenn's analysis to the case of large conversion efficiency, which would involve depletion of the fundamental.

(2) The use of the short pulse Nd:YAG laser to investigate, on a pulsed basis, optical storage in lithium niobate. Our experimental facility also particially funded by another Research Initiation Grant.* We feel that this approach can lead to a significant understanding of the optical storage process. The second harmonic of Nd:YAG lasers has been shown recently to be effective in producing refractive index change through a multiphoton process. [27]

---

* T. K. Gaylord, NSF Grant No. GK-37453.

V. PERSONNEL

The grant has provided partial support for the principal investigator, and has involved two graduate students and one undergraduate special problem student. The grant has directly aided the researcher in fundamental understanding, which has resulted in an undergraduate textbook. [28] In addition, a tutorial description and conference presentation of several basic types of laser beam communication systems was published during the duration of the grant and is attached as Appendix A. [29]

APPENDIX A

A SURVEY OF APPLICATIONS OF LASER BEAM LINKS

by

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School of Electrical Engineering
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Atlanta, Georgia

Presented to

Protective Relaying Conference
May 4-5, 1972

A SURVEY OF APPLICATIONS OF LASER BEAM LINKS

Since the first successful operation of a ruby laser by Maiman in 1960, optical communication has been one of the prime applications mentioned for the laser by researchers in the field. At this time we are only beginning to see the fruition of a decade of effort. Several excellent reviews[1-3] concerning the state of the art in optical communications have been published. Because of the vastness of the subject we do not wish to duplicate these efforts, but merely desire to provide an introduction to the subject and consider the prime aspects of a simple terrestial data link. Typical examples of such a link would be between relatively close portions of organizations such as hospitals, computer centers, and public utilities. The latter have need for efficient reliable communication links with limited data rates for telemetry and protective relaying.

The principal reason generally cited for optical communication systems is their tremendous bandwidth for carrying information. Due to the difference in frequency of the carrier wave, the theoretical capacity of an optical link is approximately 10^5 times that of a typical microwave system. Although this capacity is there in principal, it is not easily usable.* This fact, however, does not preclude the use of a laser for many special purpose applications where other considerations may be of significance. For example, a major specialized application which has received significant literature coverage is the use of lasers in space communications[4-5] where atmospheric interference is not a problem and the distances are enormous, with data rates and system weight more significant than total cost. An example at the opposite extreme is that of a terrestial link of extremely short distance, as between adjacent office buildings in a city.

For any communication scheme one must not only decide which basic approach to use as, for example, lasers versus microwaves, but also the best device and method within any given broad area. The choices are complex and depend

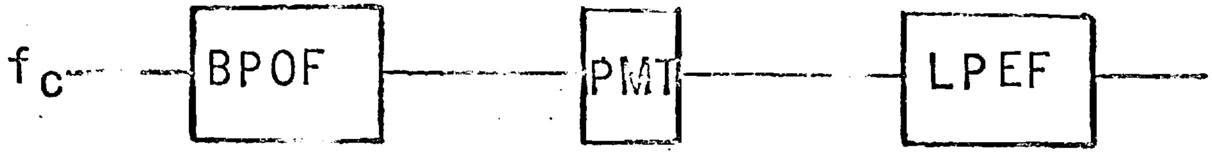
* The author would like to call attention to the October 1970 issue of the Proceedings of the IEEE, a special issue on optical communications.

on frequency, method of detection, method of transmission, type of modulation and data rate. We will look briefly at some of the choices available in each of these areas.

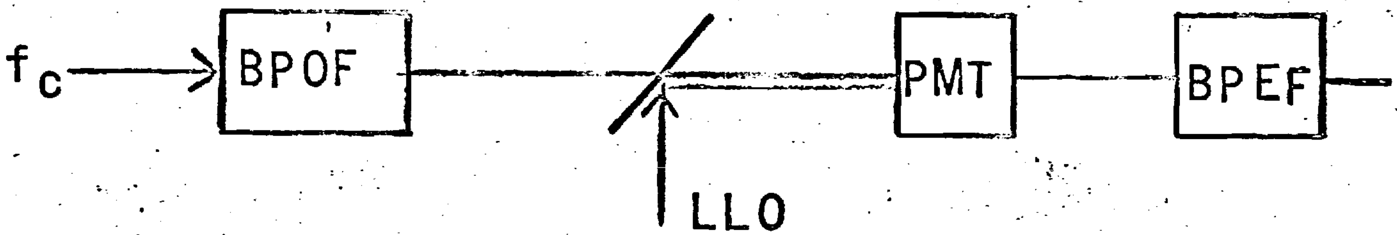
There are three basic communication-detection schemes which may be used in conjunction with a laser transmitter. The first method, direct detection, which is the easiest to visualize, does not use the outstanding feature of the laser, its choherence. It is an intensity modulation scheme only and the signal is proportional to the square of the amplitude of the carrier wave. The other two methods, heterodyne and homodyne detection, do utilize the laser's coherency, but for terrestial systems they must pay a dear price. The major price is that the coherent systems are extremely sensitive to any aberration caused by external factors such as weather conditions. The other price, which is a monetary price, is caused by the addition of a laser local oscillator which must be locked to the transmitter.

Descriptions of these three methods are illustrated in Figure 1. In this figure, the carrier wave of frequency fc and amplitude A_c is incident from the left and passes through a band-pass optical filter (BPOF). For the direct detection scheme, the carrier is directly incident on a detector, e.g., a photomultiplier (PMT), and the information is conveyed by changes in signal intensity after passage through a low-pass electrical filter (LPEF). In the other two schemes, the carrier frequency is mixed with that of a laser local oscillator (LLO) and both waves are incident on the detector. In the heterodyne method, information is conveyed by the difference in frequency, $f_c - f_o$, between the carrier and the LLO. This difference frequency is passed by the band-pass electrical filter (BPEF). In the homodyne method, phase difference is used and the signal is electrically low-pass filtered (LPEF) prior to decoding. At present, although the choice is not always simple, it appears that the direct detection scheme is in favor, in particular with a pulse-coded format[6], which consists of time slots at regular intervals, with information conveyed by the presence or absence of a pulse in each time slot. Heterodyne detection is principally considered at far infrared wavelengths, as that of a carbon-dioxide laser operating at 10.6 μm.

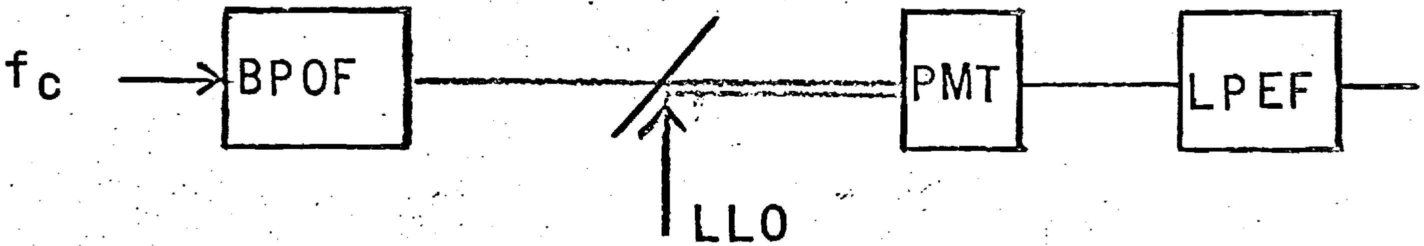
For transmission of an optical signal, a designer is faced with a binary decision -- whether to use atmospheric propagation or to employ some sort of



a. Direct Detection $I_s = \dfrac{D A_c^2}{2}$



b. Heterodyne $I_s = D A_c A_o \cos\left[(W_o - W_c)t + (\varphi_o - \varphi_c)\right]$



c. Homodyne $I_s = D A_c A_o \cos\,(\varphi_o - \varphi_c)$

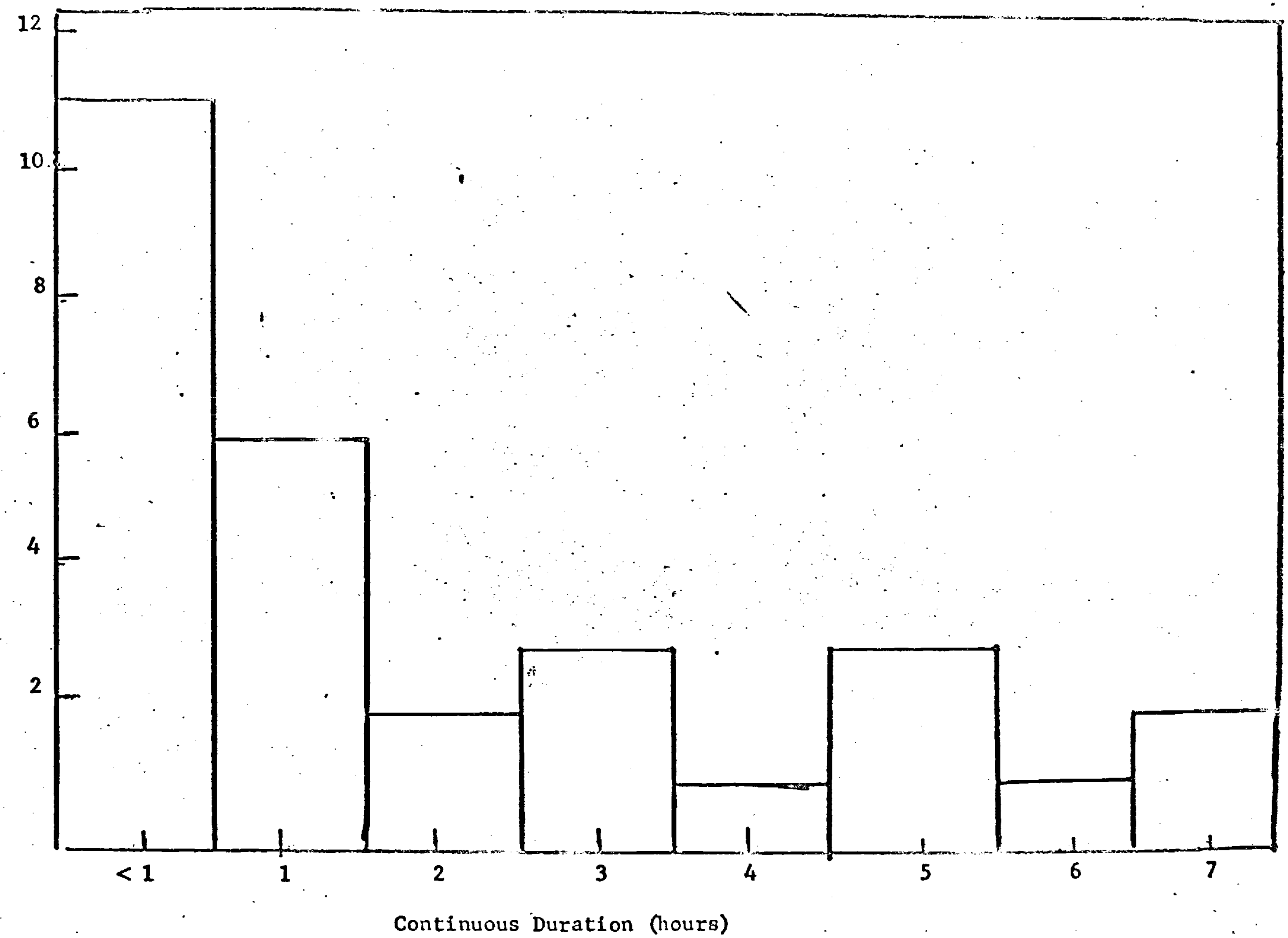
Figure 1

optical waveguide shielded from the elements. Although line-of-sight atmospheric transmission is appealing, for systems requiring high reliability for distances greater than several miles, lasers do not appear attractive yet. Although they have much smaller beam divergencies and possess the potential for higher data rates than microwave systems, lasers suffer greatly from fog and rain. This degradation of performance in adverse weather conditions is exceptionally disadvantageous for utility applications because when transmission may be most necessary, a laser system is most prone to fail.

An interesting theoretical study of laser transmission in the metropolitan Atlanta area has been performed[7]. This study indicates that for a gallium arsenide diode laser transmitter, a fog of visibility less than one-half mile would also make transmission impossible for a distance greater than one-half mile. A fog of this density would be expected to occur seventy hours out of the year on the average based on a ten year weather study (1951-1961). A histogram showing the average number of hours of continuous duration fog for a selected six month period is shown in Figure 2.* Under optimal weather however, the transmission range is much greater. A graph of laser power versus range is shown in Figure 3. We see that for a 10 watt laser transmitter, the maximum range with no fading margin is approximately ten miles. Several waveguide approaches are available. One approach is to align a series of converging lenses inside a hollow pipe. This approach presents many difficulties. The system must be precisely aligned and the lenses must be relatively closely spaced if a curved path is to be followed. In order to evade the above problems, Bell Telephone Laboratories has extensively investigated the properties of a gas lens transmission system. In this system the pipe is filled with gas and the outside of the pipe heated. When the gas is flowed through the tube, an equilibrium situation is achieved with denser gas in the center of the tube. The effect is that of a converging lens. The difficulty with this method is that aberrations are introduced into the beam and it is also an expensive system to incorporate unless a very high data rate is required.

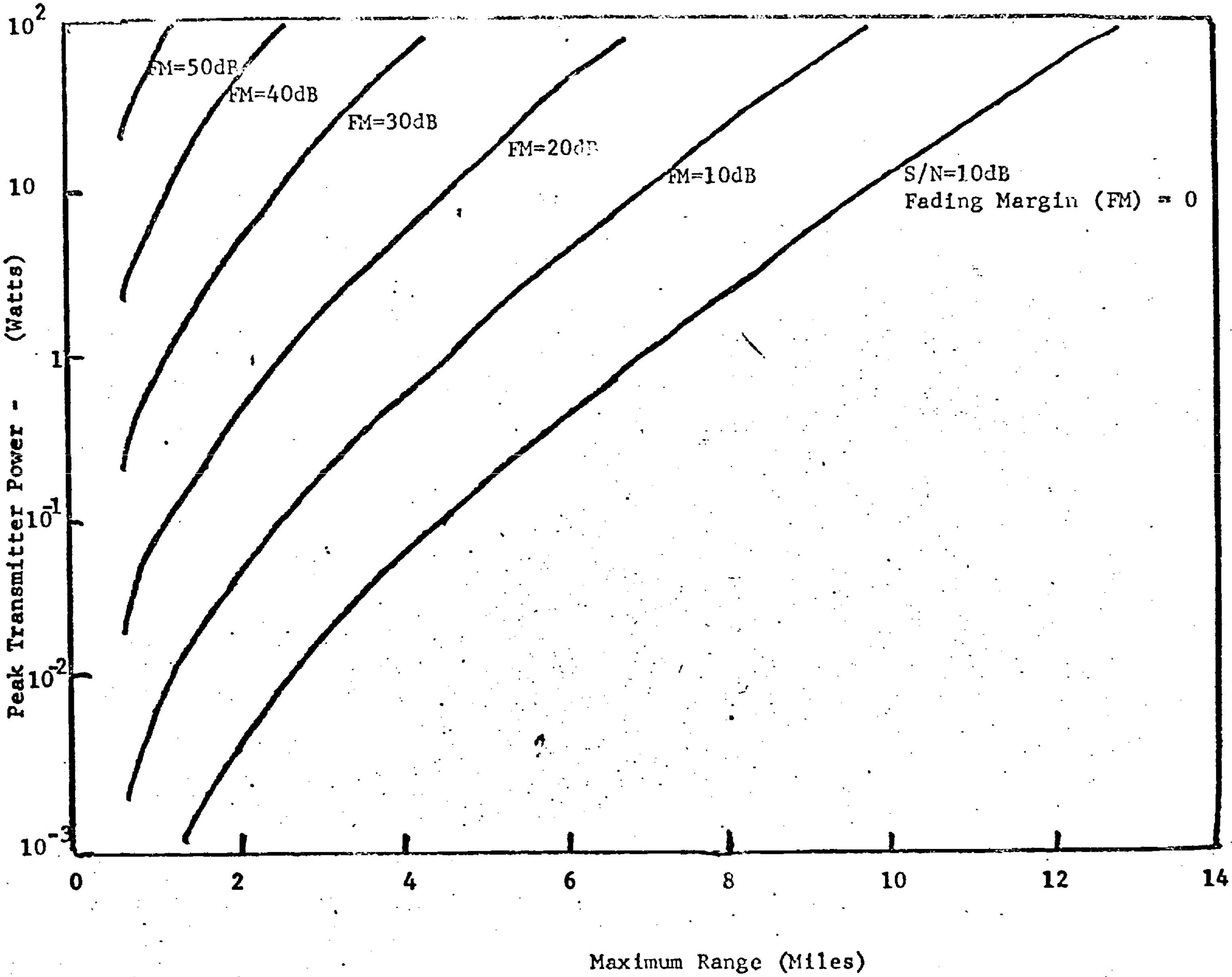
The most promising waveguide approach is fiber optics. Bell Laboratory scientists have recently announced[8-9] development of a fiber with losses as

* Figures 2, 3, and 4 were taken by permission from reference #7.



Continuous Hours Duration of Low Visibility Fog (< ½ Mile) during July-December 1964

Figure 2



Maximum Range for a GaAs Laser Telemetry Link Under Optimum Atmospheric Conditions

Figure 3

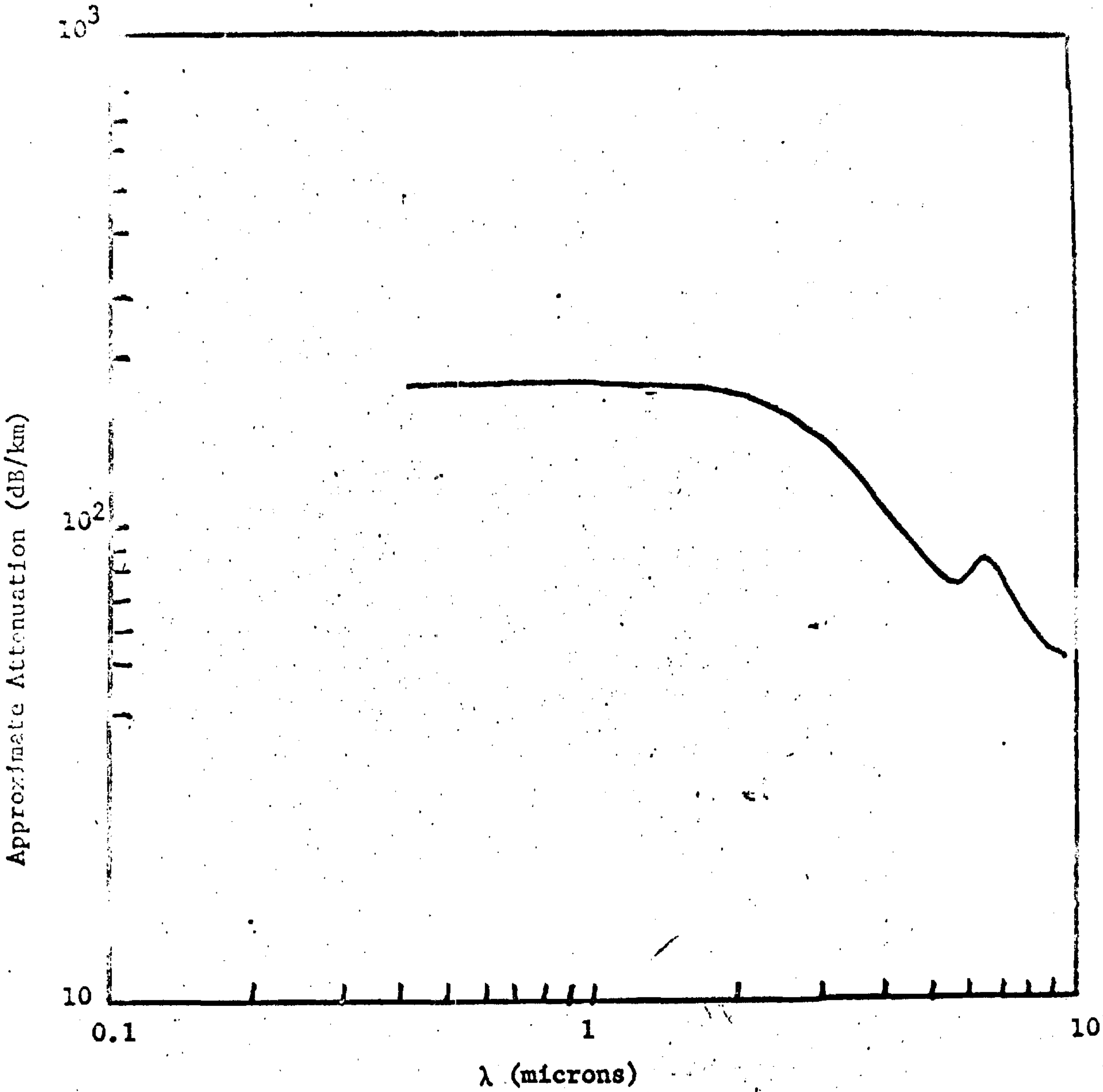
low as 13.5 db/km at a wavelength of 1.08μ and approximately 28 db/km at the wavelength of commercially available gallium arsenide diode lasers. These numbers are almost an order of magnitude better than that achievable in 1970. Further breakthroughs and refinements could make fiber optics the overwhelming choice for communication links longer than one kilometer.

The choice of type of laser and modulation scheme are closely interrelated. As seen in Figure 4, the attenuation by fog does not vary greatly throughout the visible and near infrared portion of the spectrum. Because the power output of semiconductor lasers is proportional to the current passing through them, they are extremely suitable for direct detection communication systems[10-11]. They are small, rugged and possess high efficiency operation. For these reasons they are generally the prime choice for telemetry and data link applications.

It seems that one relatively simple application for an optical link which is just beginning to achieve wide usage is that of extremely short distance special purpose applications. For the utility industry this could be a link between a sensor on a transmission line and a ground microwave system. Even in the presence of heavy fog, such a system could have a reliability approaching 100%. It would be cheap, of small size, and would provide a no-contact link between sensor and the ground-based system. A one kilometer path length computer system link at the University of Colorado in Boulder[12] was reported. The total system cost was extremely low with most components costing less than $50.00 each. In one and one-half years of operation, only one failure in a heavy snow storm was reported. Similar systems have been reported elsewhere[13].

In addition to very close range data links, systems on the order of several miles requiring high data rates and less than 100% reliability are feasible. The city of Cleveland has been investigating a color TV link over a 1½ mile path between Cuyahoga County House of Correction and the Highland View Hospital[14]. A helium-neon laser is used at a total system cost of $29,000.

Most of the small diode systems we have discussed operate at a bit rate of approximately fifty kilobits per second but, with advantageous coding schemes, are capable of 150 megabits per second.[11]



Calculated Attenuation in a Fog of Water Density 0.1 g/m^3 for the Spectral Region 0.4-10μ.

Figure 4

In Sunnyvale, California, Lockheed has a large argon laser system sending data over a 1.2 mile path at the rate of 300 megabits per second.[15] It seems that as the data rate requirement increases and technology improves, more optical links will appear.

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